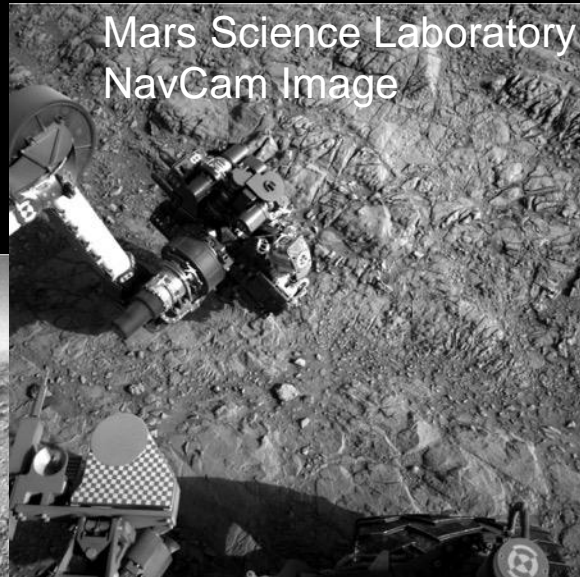


Flexible Camera architecture for generic space imaging applications

Low-Cost Planetary Missions Conference, Pasadena, California



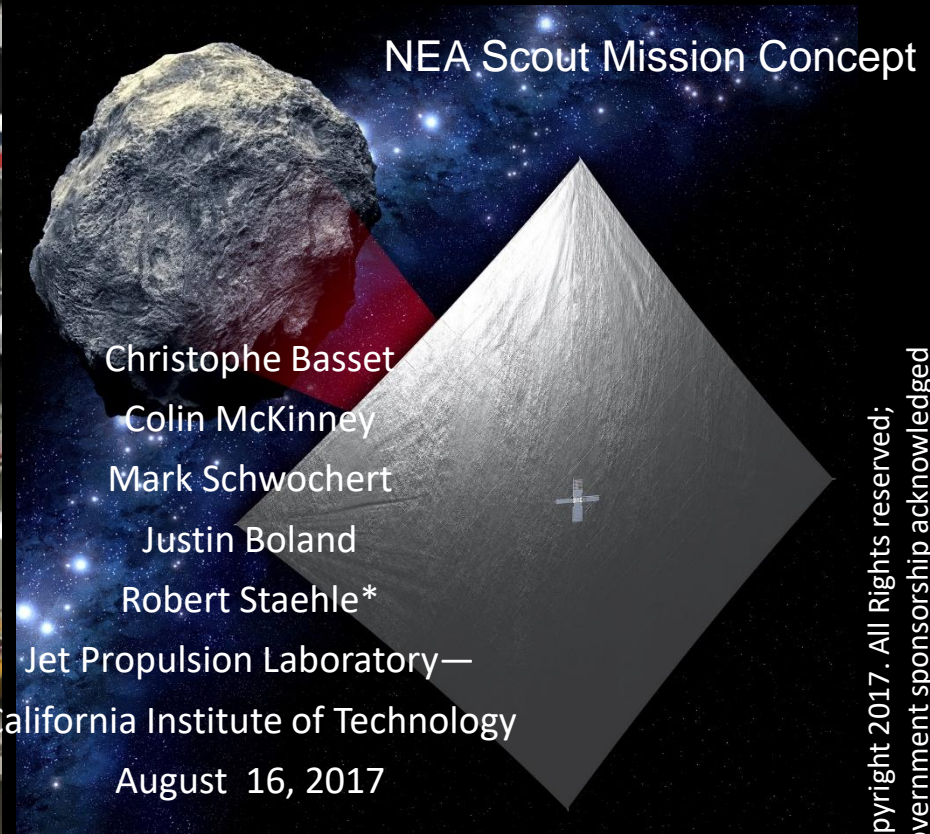
Mars Science Laboratory
NavCam Image



Mars Science Laboratory
HazCam Image



Orbiting Carbon Observatory 3
Internal Context Camera



NEA Scout Mission Concept

Christophe Basset

Colin McKinney

Mark Schwochert

Justin Boland

Robert Staehle*

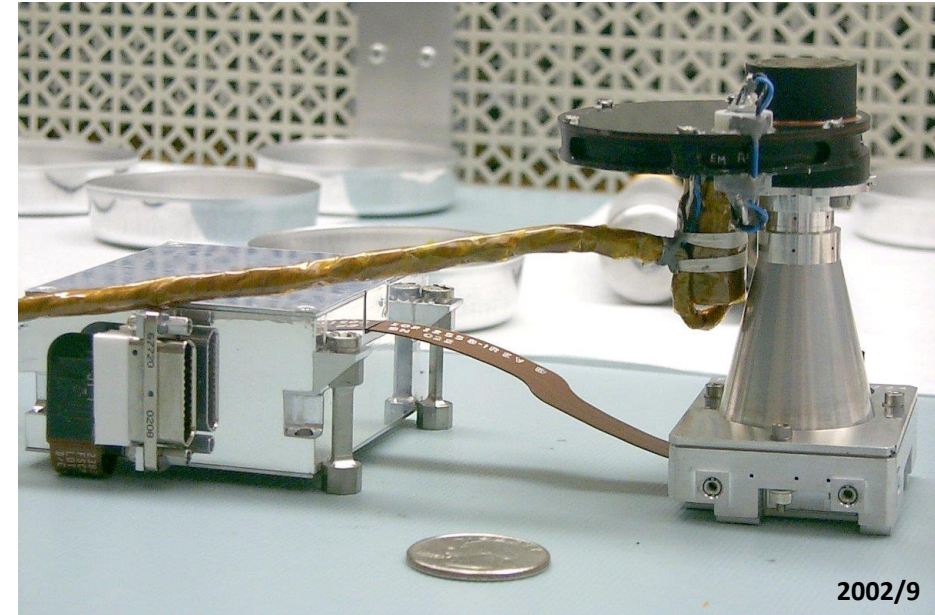
Jet Propulsion Laboratory—
California Institute of Technology

August 16, 2017

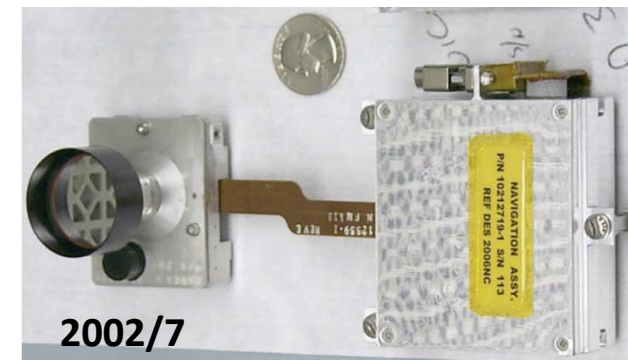
Why does NASA pursue custom camera developments?

- Demanding Science/engineering performance requirements
 - High resolution, large format detectors
 - Sensitivity/SNR/Wavelength Cutoff Requirements
 - Tailored Image processing
- Environmental screening (mission assurance)
 - Radiation, wide-temperature operation, assembly techniques
 - Parts screening, derating, performance across temperature

Takeaway: NASA has a need for adaptable, scalable camera architecture that can evolve with different mission requirements



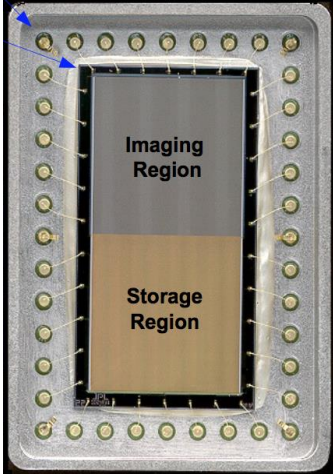
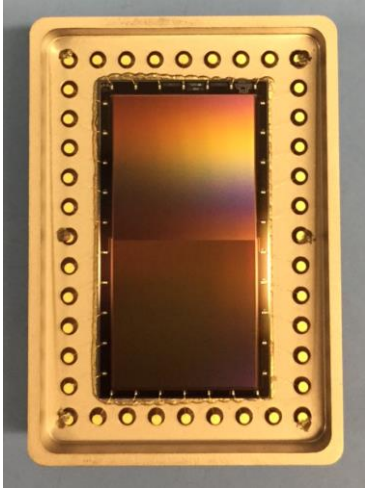
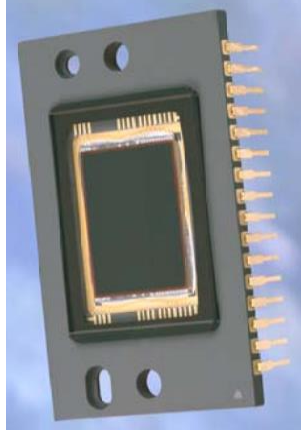
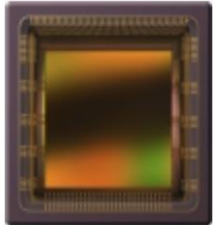
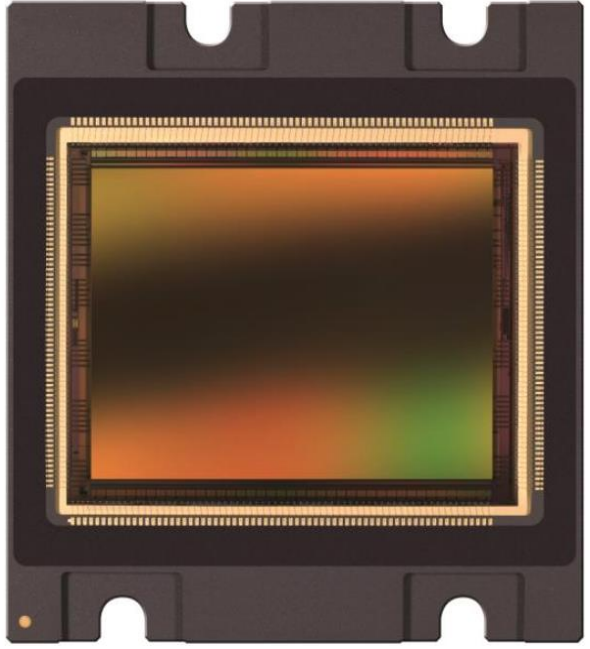
MER Pancam (shown as flown) with as-flown electronics, 8-position filter wheel, with optics to be modified from $16^\circ \times 16^\circ$ FOV to $5.5^\circ \times 5.5^\circ$ FOV.



**MER
Navcam**

Present and future detectors on JPL/NASA Planetary Cameras

Relative scales preserved

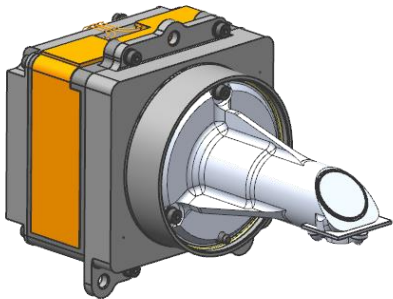
CUSTOM		COTS	
<p>Custom JPL designed and fabricated detector 1k x 1k mono CCD</p> 	<p>Custom JPL designed and fabricated detector 1k x 1k CCD, Bayer CFA</p> 	<p>Kodak TrueSense/ON Semi KAI-2020 1640x1214 RGB CCD</p> 	<p>CMOSIS CMV4000 2048x2048 RGB CMOS</p> 
<p>MER, MSL (Engineering cameras) 2003-2012</p>	<p>Insight IDC/ICC (2018)</p>	<p>Curiosity MastCam (2012), M2020 Mastcam-Z (2020)</p>	<p>M2020 SuperCam RMI (2020)</p>
			<p>CMOSIS CMV20000 5120x3840 RGB/Monochrome CMOS</p> 
			<p>M2020 Engineering cameras (2020)</p>

Mars2020 Enhanced Engineering Cameras (EECAM)

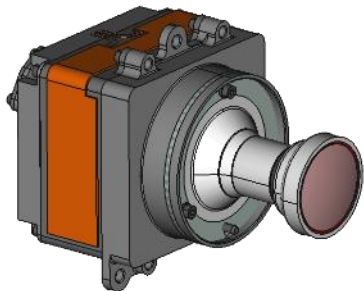
- Successor to MER/MSL Engineering Cameras
- Mission-critical imaging system (Class B hardware)
- Extensive hardware screening and qualification program
- To lower schedule risk, Mars2020 chose to baseline a **COTS focal plane array** (screened at JPL)
 - Departure from historical Class B imaging system developments
 - Characterization over environments
 - Radiation testing

Key: Significant NRE in the development of EECAM can be infused for future camera systems

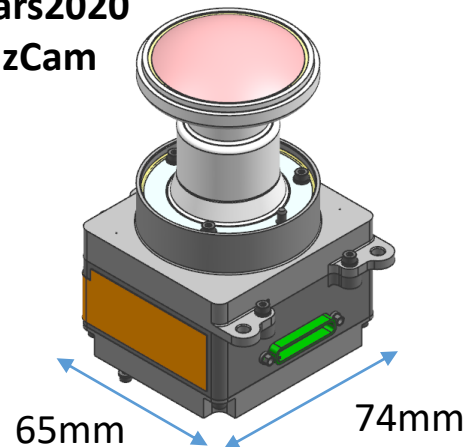
Mars2020 CacheCam



Mars2020 NavCam



Mars2020
HazCam



Mars2020 EECAM Camera Specifications

Sensor Capabilities	
Type	20M Pixel CMOS Image Sensor
Array Size	5120 x 3840
Pixel Size and Pitch	6.4 μ m ² on 6.4 μ m Pitch
Full well charge	15ke ⁻
Pixel Dark Noise	8e ⁻ RMS
Windowing	Yes
Shutter	Global
Color	Bayer RGB Color
Pixel Quantization	12bit
Electrical Interface	
Commanding & Data	LVDS
Protocol	MER/MSL/Mars2020 NVMCAM
Power Input	+5.5V (+/- 0.4V)
Power	< 3 W
Memory	1Gbit SDRAM
FPGA	MicroSemi Rad-Tolerant ProASIC3
Camera Specifications	
Mass (CBE, no optics)	< 425g
Volume (CBE, no optics)	65 mm x 75 mm x 55 mm
Operating Temperature Range	-55C to +50C
Survival Temperature Range	-135C to +70C
Optics Configurations	
Navigation Camera	95°X 71°(H x V), f/12, iFOV \leq 0.32 mrad/pix
Hazard Camera	134°X 110°(H x V), f/12, iFOV \leq 0.46 mrad/pix
Sample Caching System Camera	0.49 magnification, 130mm stop to plane-of-focus, +/- 5mm Depth of Field

Mars2020 EECAM Camera Specifications

Sensor Capabilities

Type	20M Pixel CMOS Image Sensor
Array Size	5120 x 3840
Pixel Size and Pitch	6.4um ² on 6.4um Pitch
Full well charge	15ke ⁻
Pixel Dark Noise	8e ⁻ RMS
Windowing	Yes
Frame Rate	0.45 Frames/sec
Shutter	Global
Color	Bayer RGB Color
Pixel Quantization	12bit

Electrical Interface

Commanding & Data	LVDS
Protocol	MER/MSL/Mars2020 NVMCAM
Power Input	+5.5V (+/- 0.4V)
Power	< 3 W
Memory	1Gbit SDRAM
FPGA	MicroSemi Rad-Tolerant ProASIC3

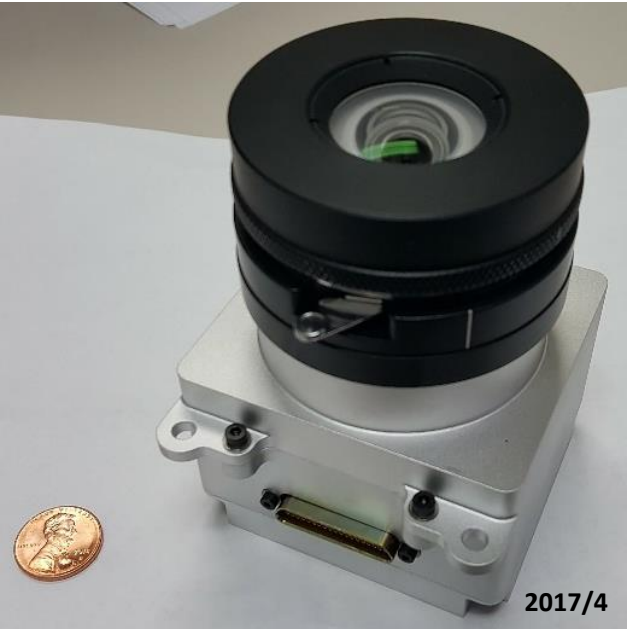
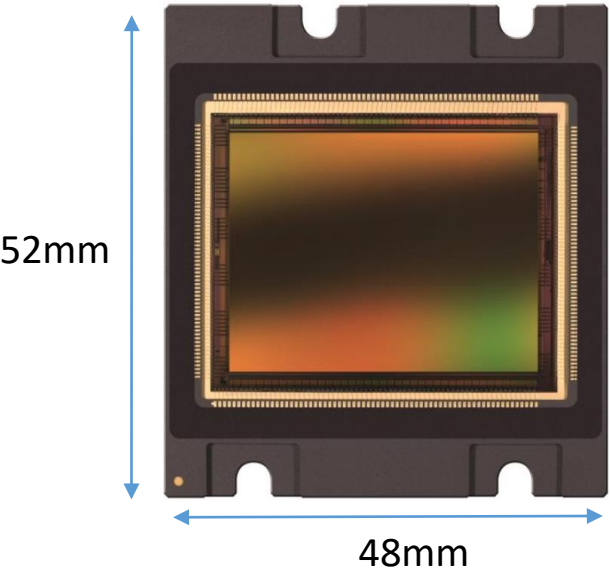
Camera Specifications

Mass (CBE, no optics)	< 425g
Volume (CBE, no optics)	65 mm x 75 mm x 55 mm
Operating Temperature Range	-55C to +50C
Survival Temperature Range	-135C to +70C

Optics Configurations

Navigation Camera	95°X 71°(H x V), f/12, iFOV ≤ 0.32 mrad/pix
Hazard Camera	134°X 110°(H x V), f/12, iFOV ≤ 0.46 mrad/pix
Sample Caching Camera	0.49 magnification, 130mm stop to plane-of-focus, +/- 5mm Depth of Field

CMOSIS CMV20000



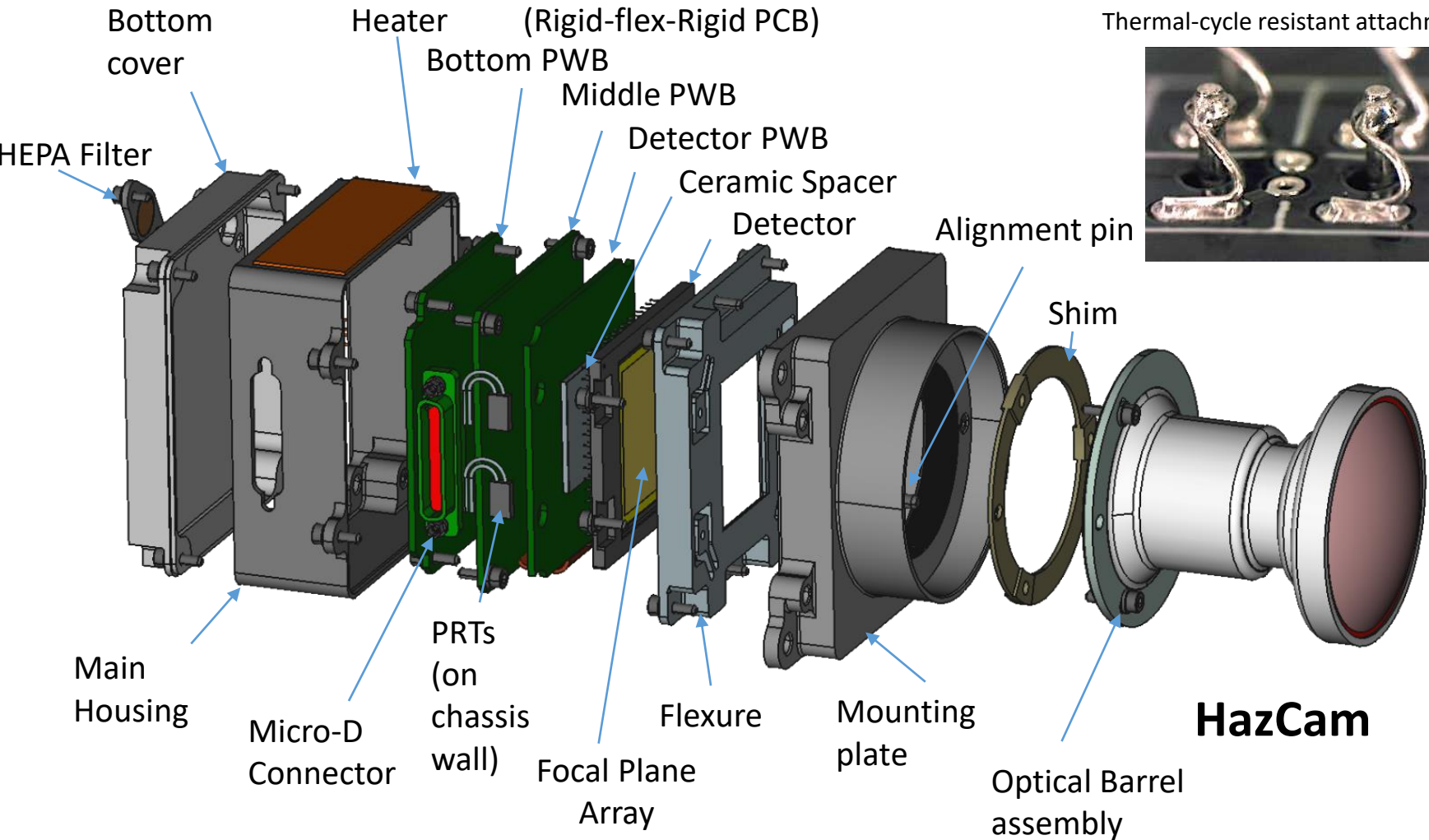
Mars2020 EECAM Engineering Development Unit

M2020 EECAM Hardware Development Team

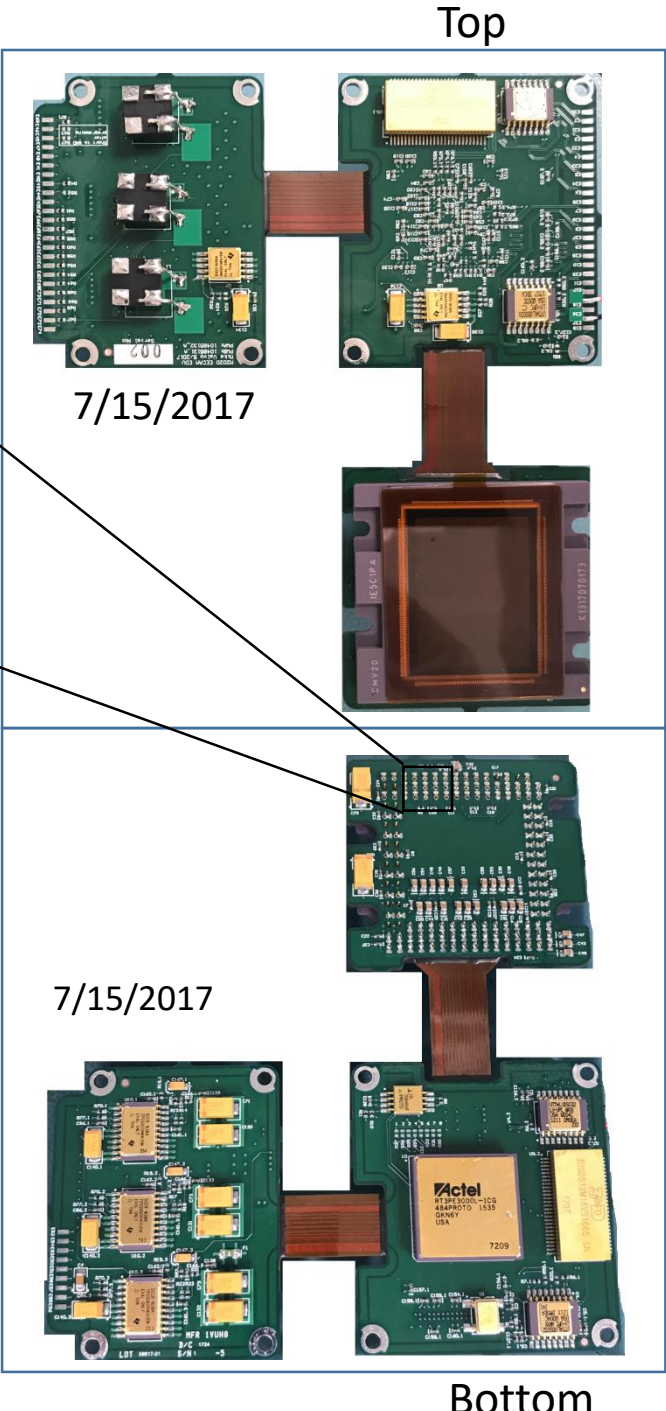


* Taken with
EECAM prototype,
2/16/2017

Mars2020 EECAM Camera Design



Thermal-cycle resistant attachment



HazCam

Mars2020 EECAM Environmental Test Levels

Thermal Performance and Test Levels

		NavCam (°C)	HazCam (°C)	CacheCam (°C)	
Protoflight (PF) or Qual		Non-Operating	70	70	70
		Operating	70	70	70
		Non-Operating	55	55	55
		Operating	55	55	55
	Allowable Flight (AFT)	Non-Operating	50	50	50
		Operating	50	50	50
		Non-Operating	-128	-128	-128
		Operating	-55	-55	-55
		Non-Operating	-133	-133	-133
		Operating	-60	-60	-60
		Non-Operating	-135	-135	-135
		Operating	-70	-70	-70

Packaging Qualification & Verification (PQV) Test Program

Season	Number of Cycles	Low (°C)	High (°C)	Delta (°C)
Summer	2115	-80	50	130
Winter 1	450	-115	-10	105
Winter 2	450	-110	20	130
Total	3015			

Mars2020 EECAM Environmental Test Levels

Random Vibration Test Levels

Rover Assemblies**	Frequency, Hz	Flight Acceptance Level	Qualification/ Protoflight Level
Rover Mounted Assemblies * (other than shown below)	20 - 40 40 - 450 450 - 2000 Overall	+ 6 dB/oct 0.04 g ² /Hz - 6 dB/oct 5.6 grms	+ 6 dB/oct 0.08 g ² /Hz - 6 dB/oct 7.9 grms
- RSM Mounted Components (with Fn > 120 Hz)	20 – 40 40 – 450 450 – 2000 Overall	+6 dB/oct 0.04 g ² /Hz -6 dB/oct 5.6 Grms	+6 dB/oct 0.08 g ² /Hz -6 dB/oct 7.9 Grms

Pyrotechnic Shock Test

Camera	Zone	Frequency, Hz	QUAL, PF Peak SRS Response (Q=10)
NavCam	1.4	100	14g
		100-1,600	+10.0 dB/Oct.
		1,600-10,000	1,400g
HazCam	3.5	100	49g
		100-3,000	+7.6 dB/Oct.
		3,000-10,000	3,500g
CacheCam	2	100	20 g
		100 - 1,600	+ 10.0 dB / Oct.
		1,600 - 10,000	2,000 g

EECAMs on Mars2020

EECAM Type	Units
NavCam	2
HazCam	6
CacheCam	1
Total	9

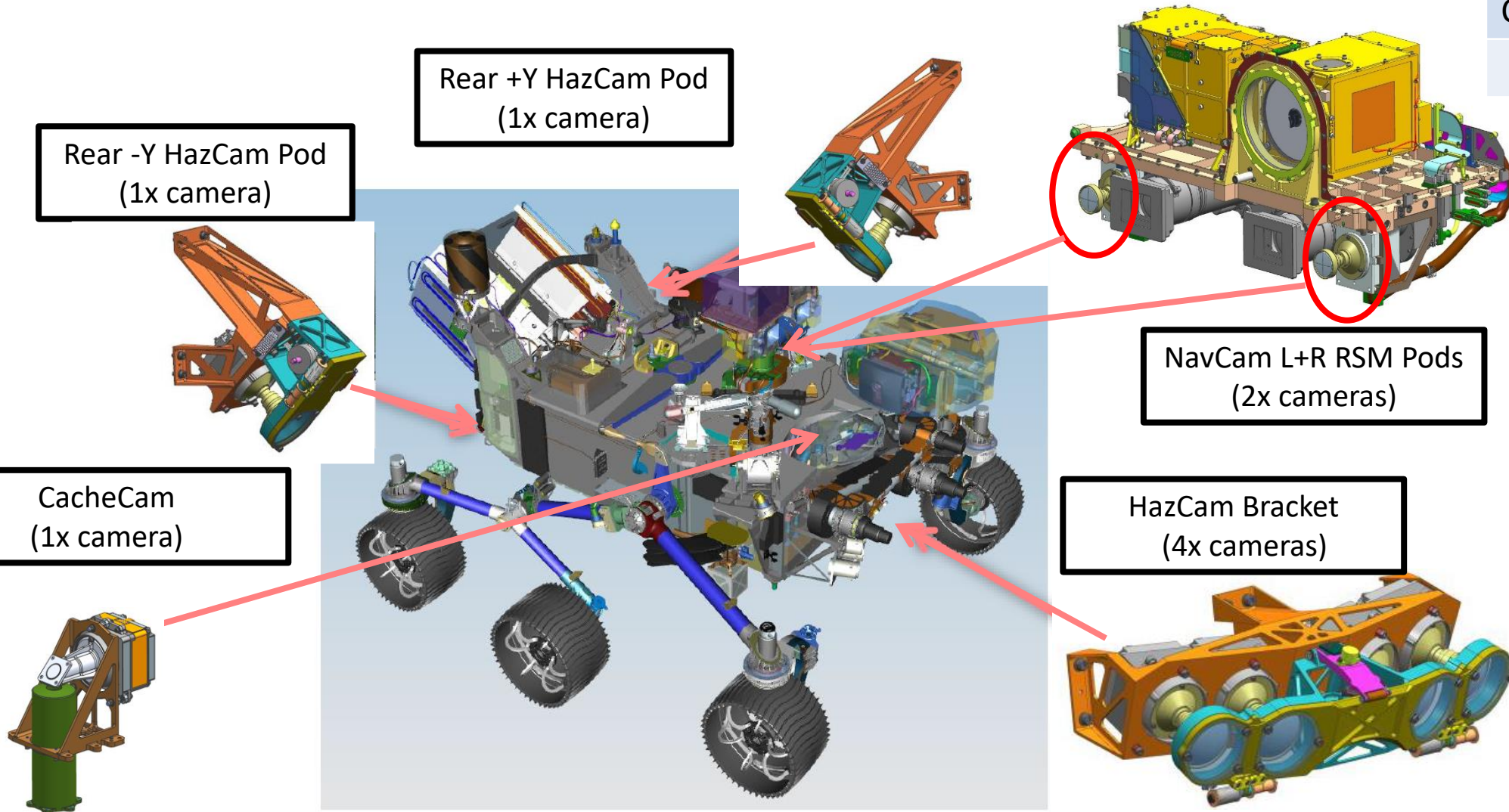
Rear -Y HazCam Pod
(1x camera)

Rear +Y HazCam Pod
(1x camera)

CacheCam
(1x camera)

NavCam L+R RSM Pods
(2x cameras)

HazCam Bracket
(4x cameras)

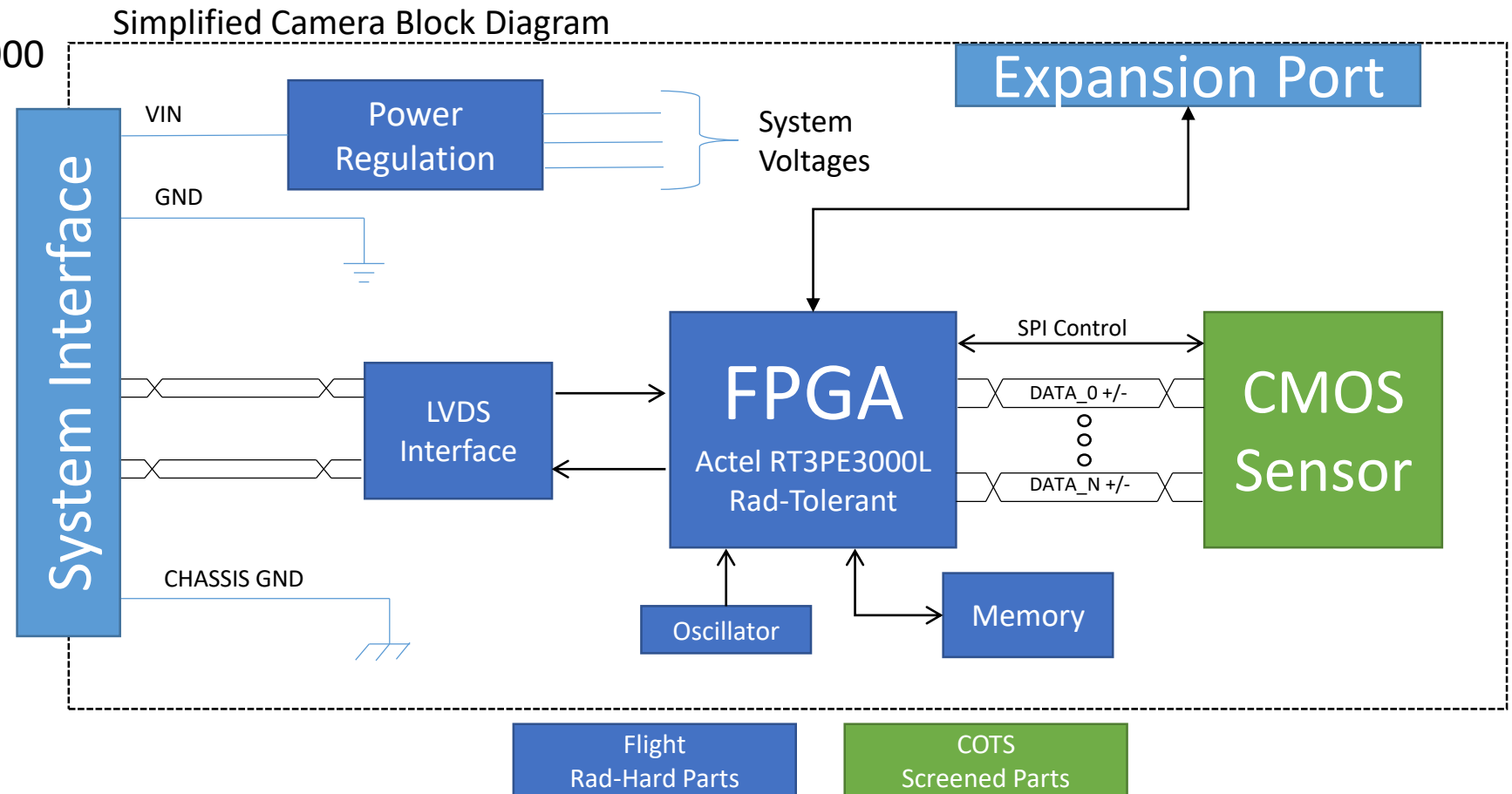


Infusing EECAM’s flexible camera architecture

Camera	Mission Class	Electronics	Optics			Development Status	Delivery Date to Mission	Mission Need Date	Mission Launch Date
			Development	Field of View	iFOV				
Mars2020 EECAM (9 FM units, 4 FS)	B	Rigid-flex, Screened EEE Parts	Custom	95° x 73°	0.35 mrad/pixel	Flight cameras being built	Oct. 2018 (Planned)	Jan. 2019	7/2020
				180° diagonal	0.55 mrad/pixel				
OCO-3 Context Cameras (2 FM units, 1 FS)	C	Discrete PCBs, plastic connectors, rad-tolerant parts	COTS C-mount (Internal), F-Mount (External)	32° x 28°	0.125 mrad/pixel	Flight cameras delivered	Apr. 2017	June 2017	2019 [TBD]
				56° x 48°	0.22 mrad/pixel				
NEAScout CubeSat (1 FM, 1 FS)	D	Discrete PCBs, plastic connectors, rad-tolerant parts	COTS C-mount	26.9° circle	0.128 mrad/pixel	Flight cameras being tested	Aug. 2017 (Planned)	Sept. 2017	2019 [TBD]
New Horizons/Discovery Proposals	B		Custom						
Future Smallsat and other proposals	B/C/D		Custom or COTS						

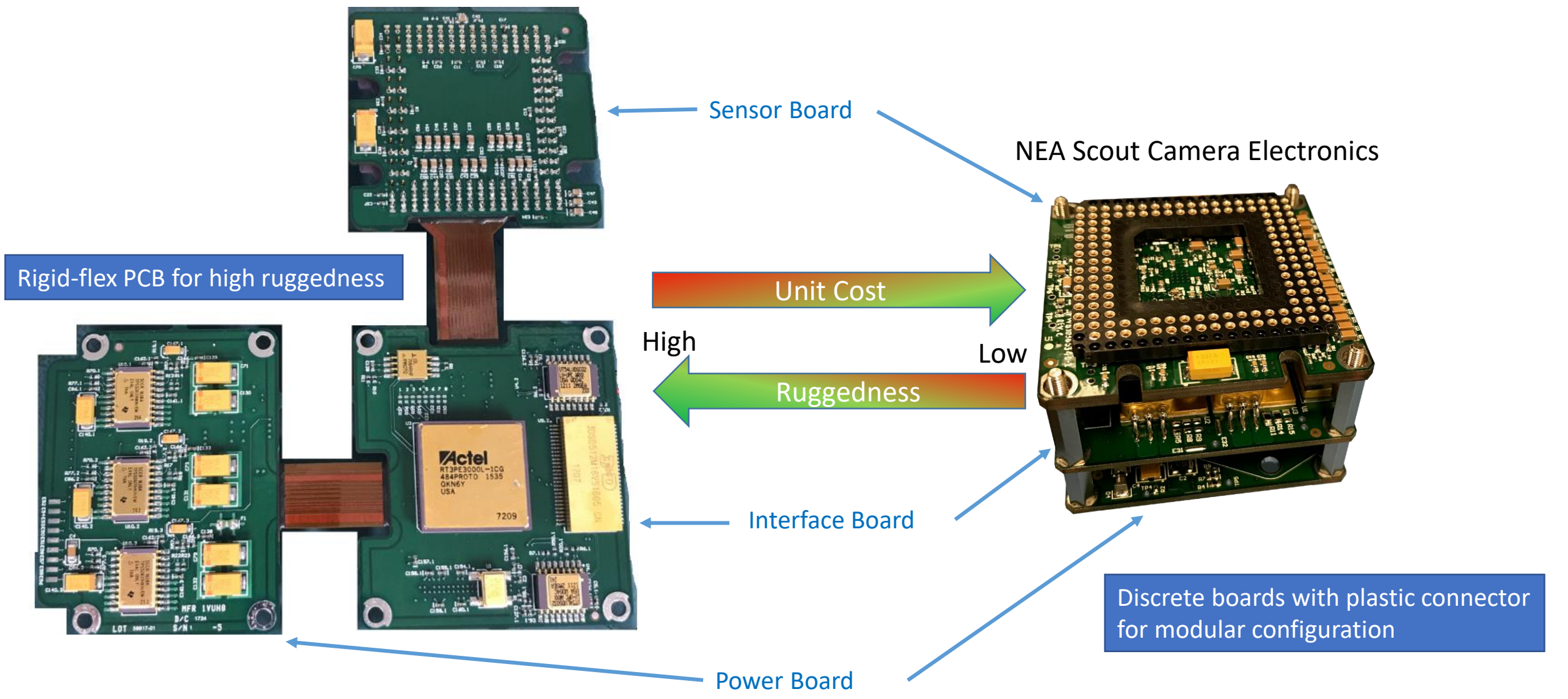
Electronics Architecture

- Reprogrammable, flash-based FPGA
- Physical form-factor/dimensions changes without significant modification to design
- Multiple data protocols over LVDS physical interface (CameraLink, SpaceWire, ...)
- Expansion Port for application-specific interfaces/hardware
- Adaptable sensor interface
 - First generation for CMV20000



Modular Electronics Implementation

Mars2020 EECAM Electronics



NEAScout Electronics

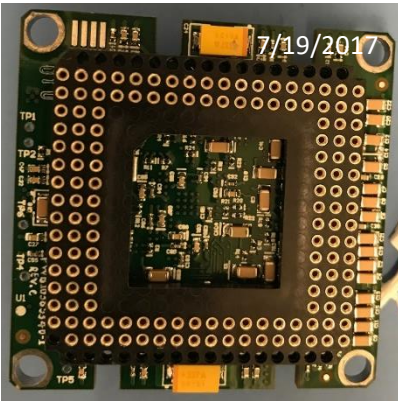
NEAScout Integrated Camera Electronics Stack
(no detector)

Sensor Board

Bottom Side



Top Side (no detector)

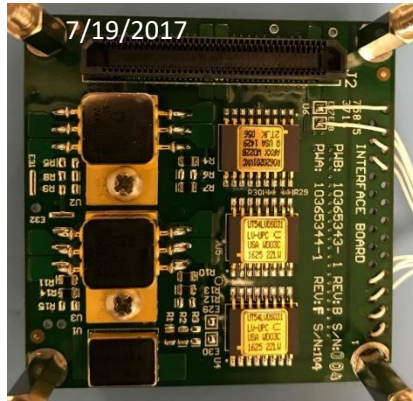


Interface Board

Bottom Side



Top Side

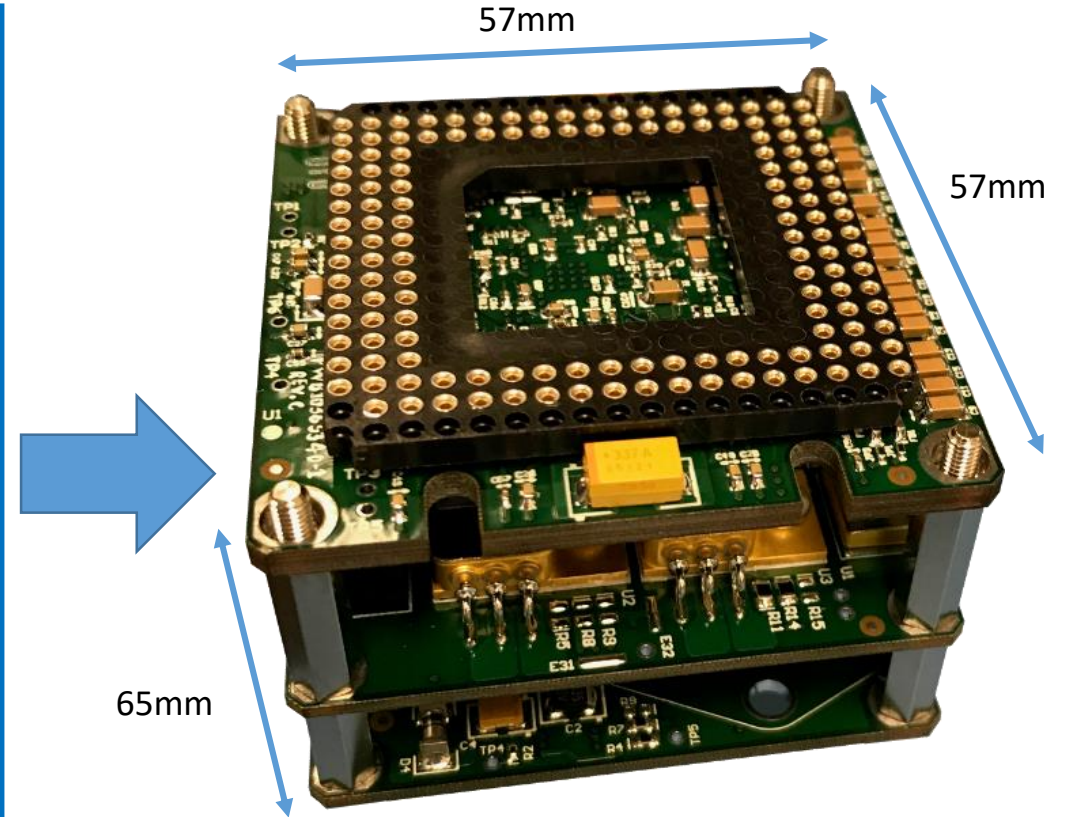


Power Board

Bottom Side



Top Side



Scalable FPGA Firmware and Data Interface

Flexible Data Interface

- Command and Telemetry interface over Low-Voltage Differential Signal (LVDS) physical layer
- Adaptable protocol options given mission interface

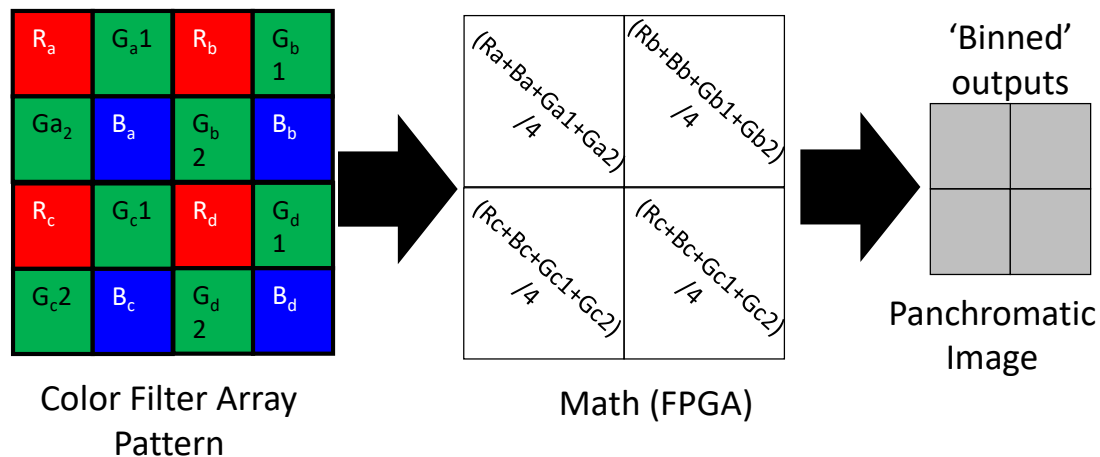
Camera	Physical Layer	Protocol
Mars2020 EECAM	LVDS	Heritage rover CMD/TLM interface
OCO-3	LVDS	Modified CameraLink
NEA Scout	LVDS	Spacewire

Scalable FPGA Firmware and Data Interface

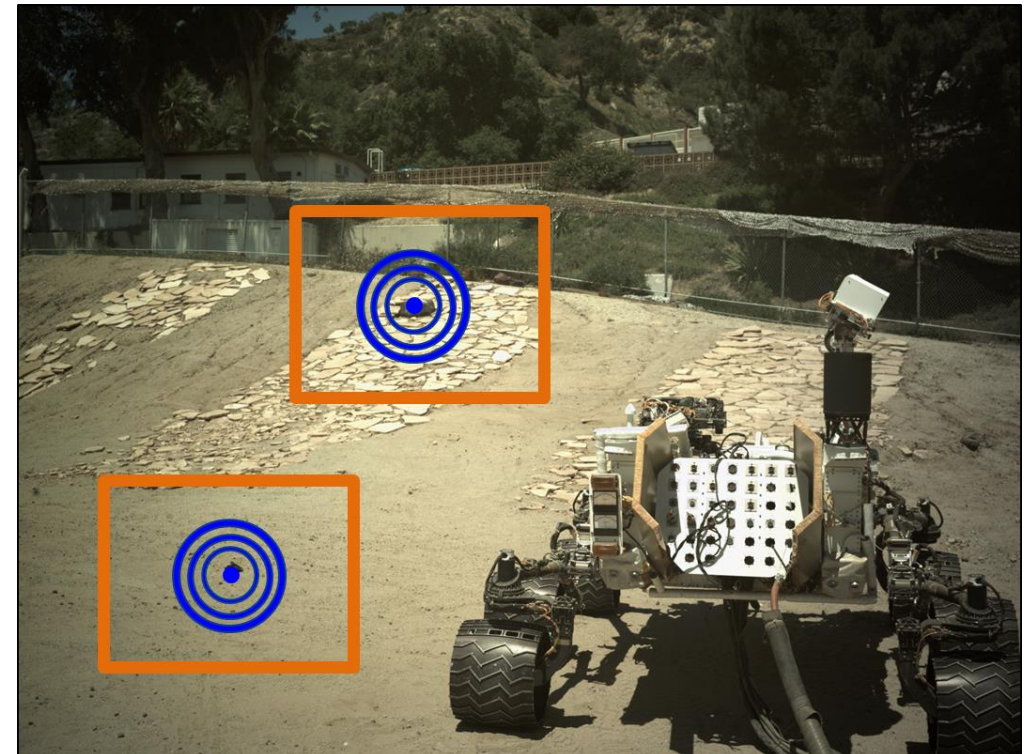
Image Processing within FPGA

- Image windowing
- Pixel binning and co-adding
 - Multiple modes supporting various binning algorithms (4x4, 2x2, ...)
 - Selectable co-addition factors to increase scene Signal-to-Noise Ratio (SNR) by adding frames
- Future possibilities
 - Color Filter Array (CFA) de-mosaic
 - Compression

2x2 Binning Mode of CFA on Mars2020 EECAM



Selectable 1280 x 960 pixel windows on Mars2020 EECAM

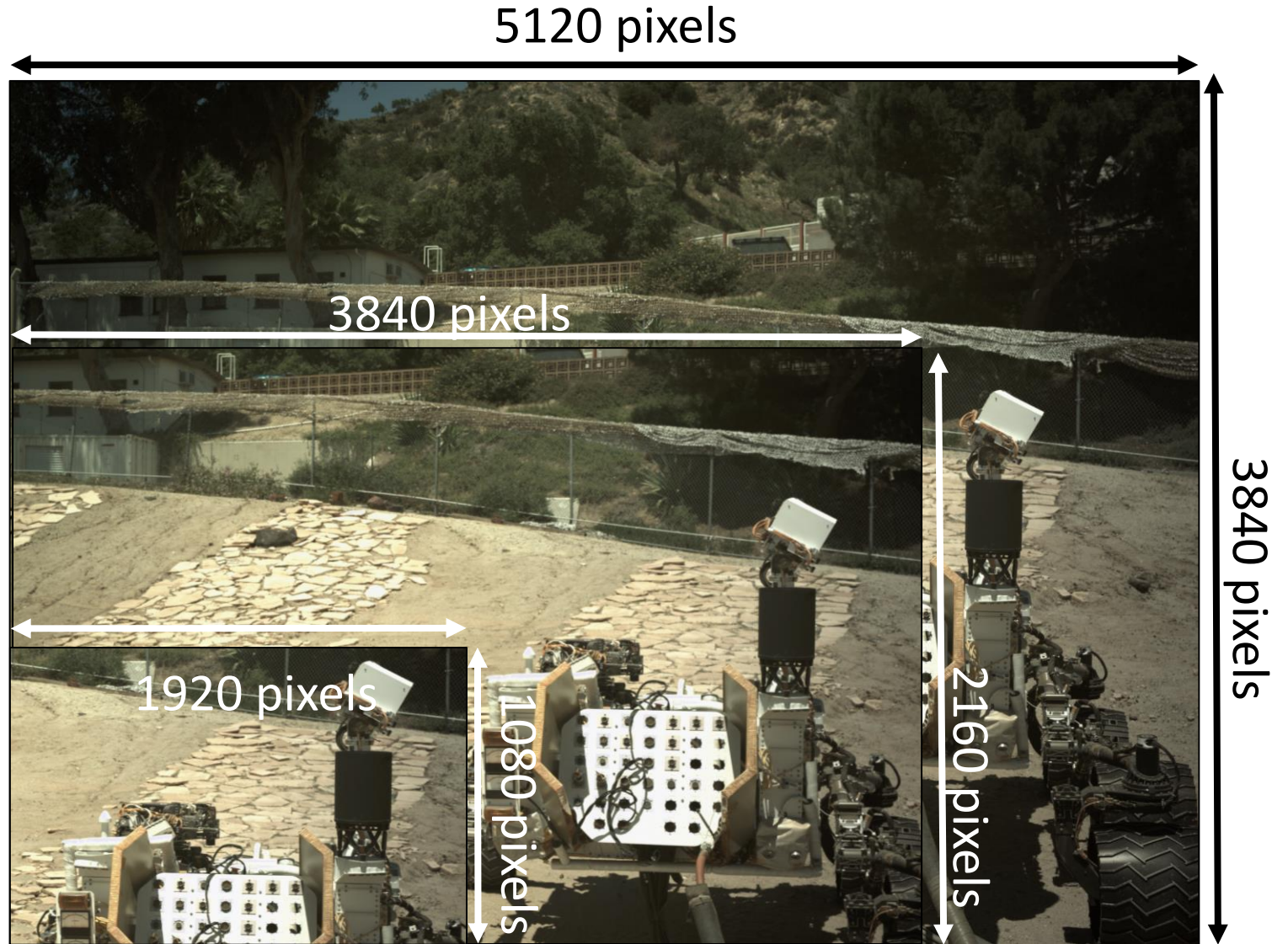


Variable Frame Size and Rate

Camera Frame size vs. Frame Rate

Frame Size (pixels)	Max. Frame Rate* (Frames/sec)
5120 x 3840 (Full frame)	4
3840 x 2160 (4k)	7
1920 x 1080 (1080p)	14

* Frame rate limited by FPGA speed and sensor readout architecture



CMV20000 Active Area

Mars2020 EECAM FPGA Resource Utilization Estimate

- Based on current design implementation

Compile Report				
Resource	Used	Total	Margin	Flight Principles
CORE	8179	75264	89%	20%
IO	120	341	65%	20%
Differential I/O	11	168	93%	20%
Global (Chip + Quadrant)	6	18	66%	20%
RAM/FIFO	8	112	93%	20%

Radiation Tolerance of Camera/Components

Rad-tolerant EEE Parts

- Latchup, SEL immune
- Depending on mission class, screened vs. unscreened flight parts can be baselined to save cost

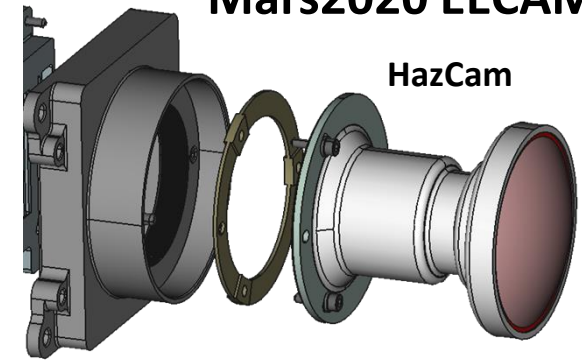
Detector radiation testing @ UC Davis and Texas A&M

- Total Integrated Dose (TID) performance well beyond Mars2020 requirements (8k TID, RDF=2)
- Latch-up – short between power rail and ground triggered by heavy ion interaction in parasitic diode structure
 - Testing at Texas A&M University Cyclotron Facility.
 - Latching behavior found **only on one voltage rail**
 - Predicted latch-up rate is 0.03 events/yr.
 - Requirement is $<10^{-4}$ events/yr
 - **Mitigation strategy is power off detector between exposures and factor in relevant detector and EECAM duty cycles**
 - **Factoring in duty cycle reduces rate to $\sim 10^{-5}$ /yr**
- Tested device latched-up hundreds of times without loss of imaging functionality – NO device failures

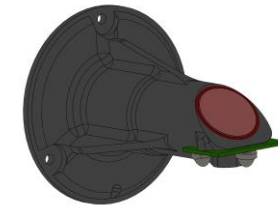
Mechanical Configurations

- Allows user to optimize camera footprint to meet constraints of mission
 - Volume, mass, shielding requirements
- Tailored packaging approach given environmental requirements
 - Deep thermal cycling vs. thermally-controlled environments
- Modular Optics mounts
 - Custom or COTS optics supported
 - Single camera electronics box design can support multiple lens configurations

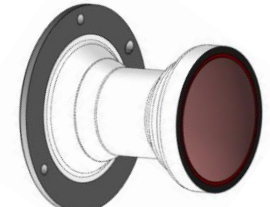
Mars2020 EECAM



Common lens interface, interchangeable lenses

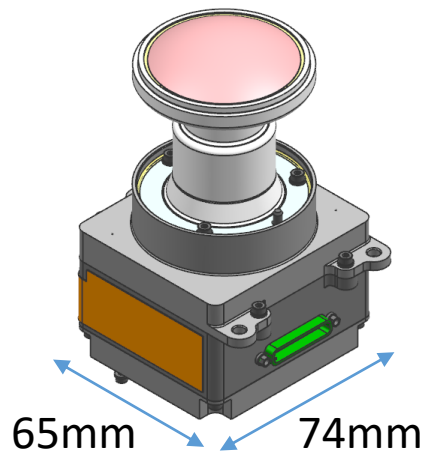
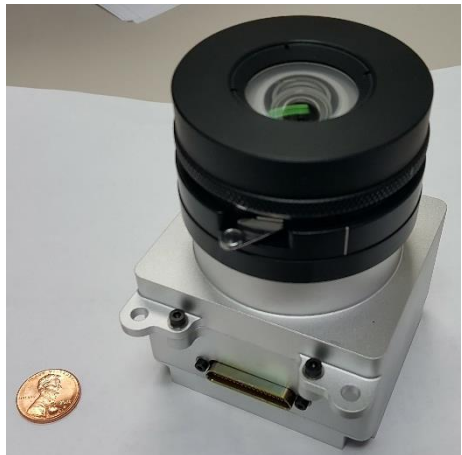


CacheCam



NavCam

Mars2020 EECAM



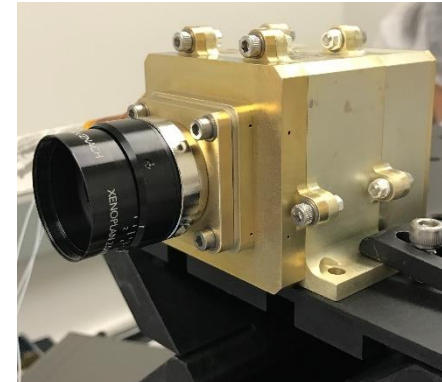
NEAScout



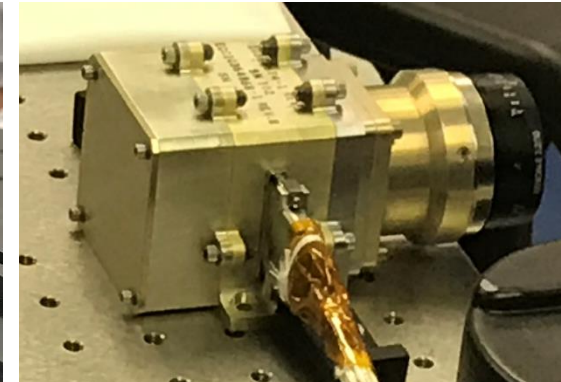
**Custom NEAScout camera chassis
(C-Mount lens)**

OCO-3 Context Cameras

Internal Context Camera (ICC)

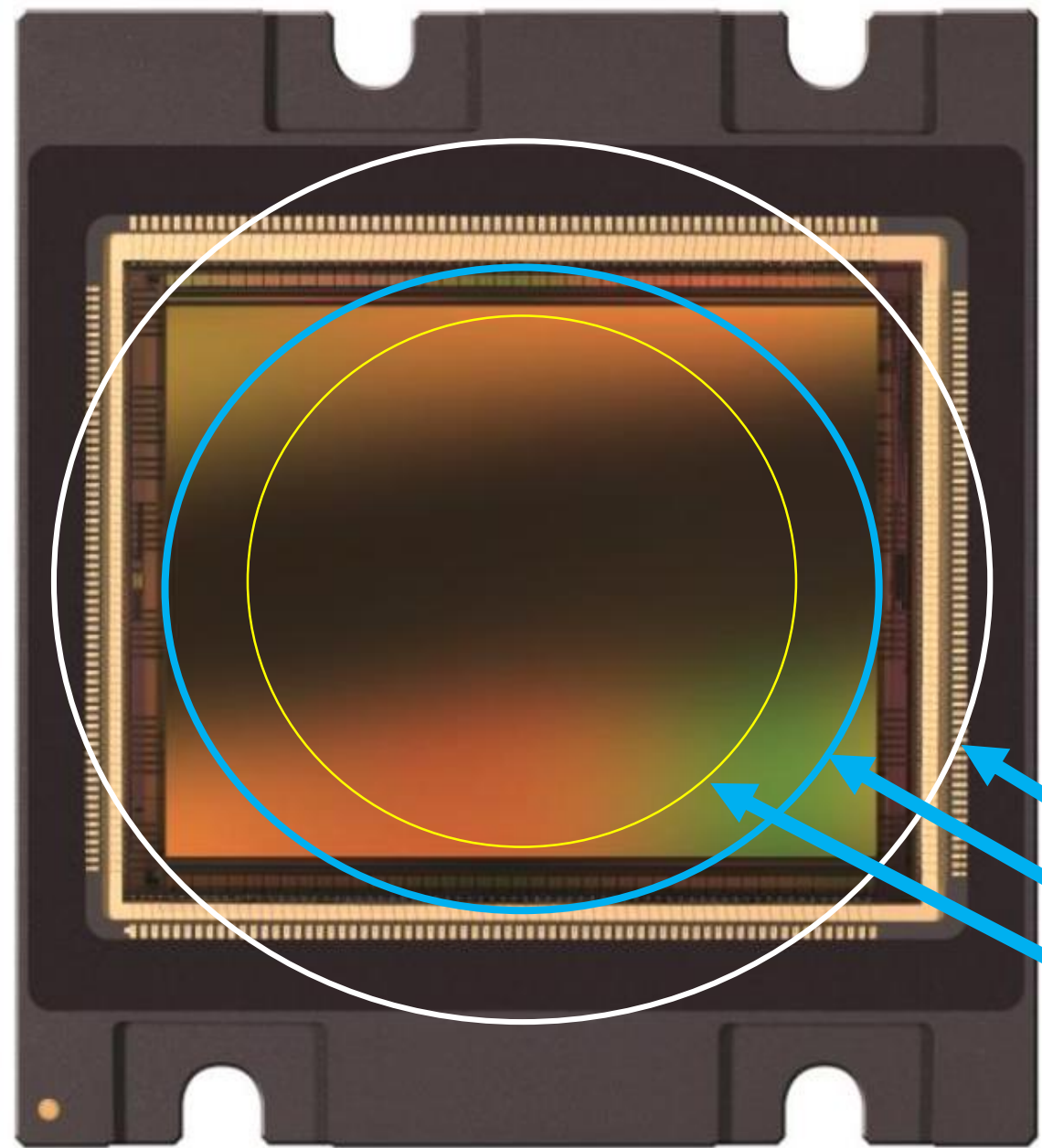


External Context Camera (ECC)



**Common camera electronics, different lenses
(C-Mount vs. F-Mount)**

Flexible Optics Configurations



Existing Optics Configurations		
Mars2020 EECAM	Navigation Camera	95°X 71°(H x V), f/12 iFOV \leq 0.32 mrad/pix
	Hazard Camera	134°X 110°(H x V), f/12 iFOV \leq 0.46 mrad/pix
Orbiting Carbon Observatory 3	Internal Context Camera	32° x 28° (H x V), f/5 iFOV \leq 0.125 mrad/pix
	External Context Camera	56° x 48° (H x V), f/2.2 iFOV \leq 0.22 mrad/pix
NEAScout	OpNav/Science Camera	26.9° image circle, f/2.8 iFOV \leq 0.128 mrad/pix

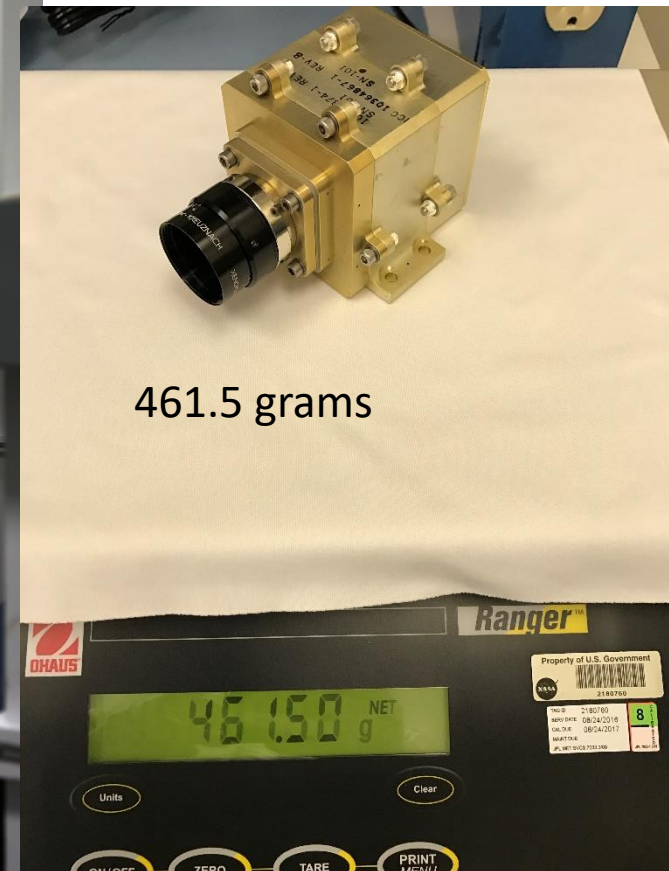
Mars2020 EECAM

OCO-3 Internal Context Camera

NEA Scout

OCO-3 Context Cameras

Internal Context Camera
Mass



*Taken with OCO-3 External
Context Camera
4/2017



External Context Camera Mass

Next Steps

- Support build-to-print or design-off-the-shelf camera developments for upcoming missions.
- Adapt electronics design to support future focal planes (e.g. CMOSIS CMV50000)
 - To go from 20M pixels to 50M pixels
- Proposal support for Science and Engineering planetary camera missions
 - New Frontiers/Discovery (Class B)
 - CubeSat or Technology Demonstration (Class D)

JPL Cost and Schedule Performance with Engineering Cameras Built for Mars Science Laboratory Curiosity

- 26 Cameras built, 12 are on Mars (Others EM & spare, 2 now to InSight).
- 9 Navcams, 17 Hazcams built, delivered under budget.
- 28 month build, delivered May 2008, vs. May 2008 planned when authorized/funded to proceed.
- 10 more cameras each aboard *Spirit* & *Opportunity*, plus 2 aboard *Phoenix*.
- Over 100,000 images and counting, as of 2017 July.
- No in-flight failures.

Front Hazard Avoidance Cameras (Front Hazcams)



Sol 456 (8 img)
Sol 455 (204 img)
Sol 454 (116 img)
Sol 453 (52 img)
Sol 443 (4 img)
Sol 442 (20 img)
Sol 441 (4 img)
Sol 440 (8 img)

Rear Hazard Avoidance Cameras (Rear Hazcams)



Sol 456 (8 img)
Sol 455 (20 img)
Sol 454 (8 img)
Sol 453 (8 img)
Sol 443 (4 img)
Sol 442 (4 img)
Sol 441 (4 img)
Sol 440 (8 img)

Left Navigation Camera (Navcams)



Sol 456 (24 img)
Sol 455 (340 img)
Sol 454 (220 img)
Sol 453 (248 img)
Sol 443 (4 img)
Sol 442 (8 img)
Sol 441 (28 img)
Sol 440 (100 img)

Right Navigation Cameras (Navcams)



Sol 456 (40 img)
Sol 455 (340 img)
Sol 454 (222 img)
Sol 453 (248 img)
Sol 443 (20 img)
Sol 442 (8 img)
Sol 441 (12 img)
Sol 440 (68 img)

Summary

Nine years on Mars. Matijevic Hill on
Endeavor Crater rim.
Mosaic from *Opportunity* Pancam Sols 3137
– 3150 (2012 /11/19 – 12/3)

Contact: robert.l.staehle@jpl.nasa.gov
818 354-1176

- Leverage COTS technologies and high-reliability packaging from Mars2020 camera development to enable low-cost cameras for planetary missions
- Modular camera architecture can be tailored to meet mission-specific requirements and resources

Navcam photo – *Curiosity* (Sol 2)

Dust devil tracked
from Mars Exploration

Rover Navcam at ~1 km
Spirit Sol 486 (2005 May 15)

100 sec elapsed time
Moving ~5 m/s
~34 m diameter

We've landed!

Front Hazcam: Right A (FHAZ_RIGHT_A)
Curiosity on Sol 0 (2012/8/6)